

(12) **United States Patent**
Schneider et al.

(10) **Patent No.:** **US 10,180,490 B1**
(45) **Date of Patent:** **Jan. 15, 2019**

(54) **RADIO FREQUENCY COMMUNICATION SYSTEM**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 633 days.

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(21) Appl. No.: **13/975,724**

U.S. Appl. No. 13/918,295, filed Jun. 14, 2013, Edward Hill (31 pages).

(22) Filed: **Aug. 26, 2013**

(Continued)

Related U.S. Application Data

(60) Provisional application No. 61/692,787, filed on Aug. 24, 2012.

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(51) **Int. Cl.**
H04W 24/00 (2009.01)
G01S 5/02 (2010.01)

(57) **ABSTRACT**

(52) **U.S. Cl.**
CPC **G01S 5/0294** (2013.01)

A system and method for recovering from a failure during the position tracking of an RF-transmitting device includes tracking the position of the radio frequency (RF) transmitting device based on RF signals emitted by the RF-transmitting device. If the tracking loses the position of the RF-transmitting device, new phase difference data are calculated from the RF signals transmitted by the RF-transmitting device and received at four or more antennas. A subset of candidate position solutions for evaluation is identified based on the new phase difference data. One or more of the candidate position solutions in the subset is evaluated to find an acceptable position solution. The tracking of the position of the RF-transmitting device resumes using the acceptable position solution.

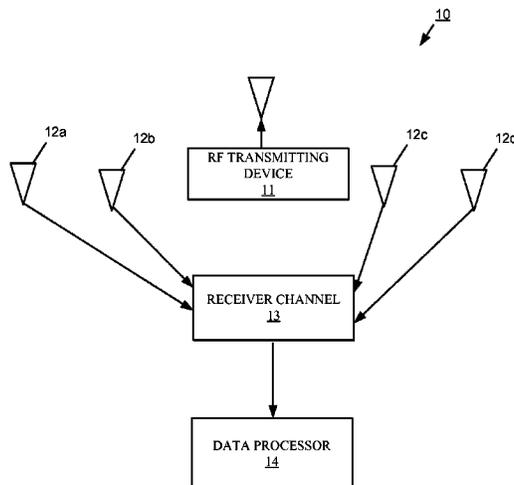
(58) **Field of Classification Search**
CPC G01S 5/0294; G01S 5/0278; G01S 5/06; H04Q 7/38; H04M 2207/18; H04M 2242/30; G08G 1/207; G08B 21/18; H04W 4/021
USPC 342/465; 455/456.1
See application file for complete search history.

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10 Claims, 4 Drawing Sheets



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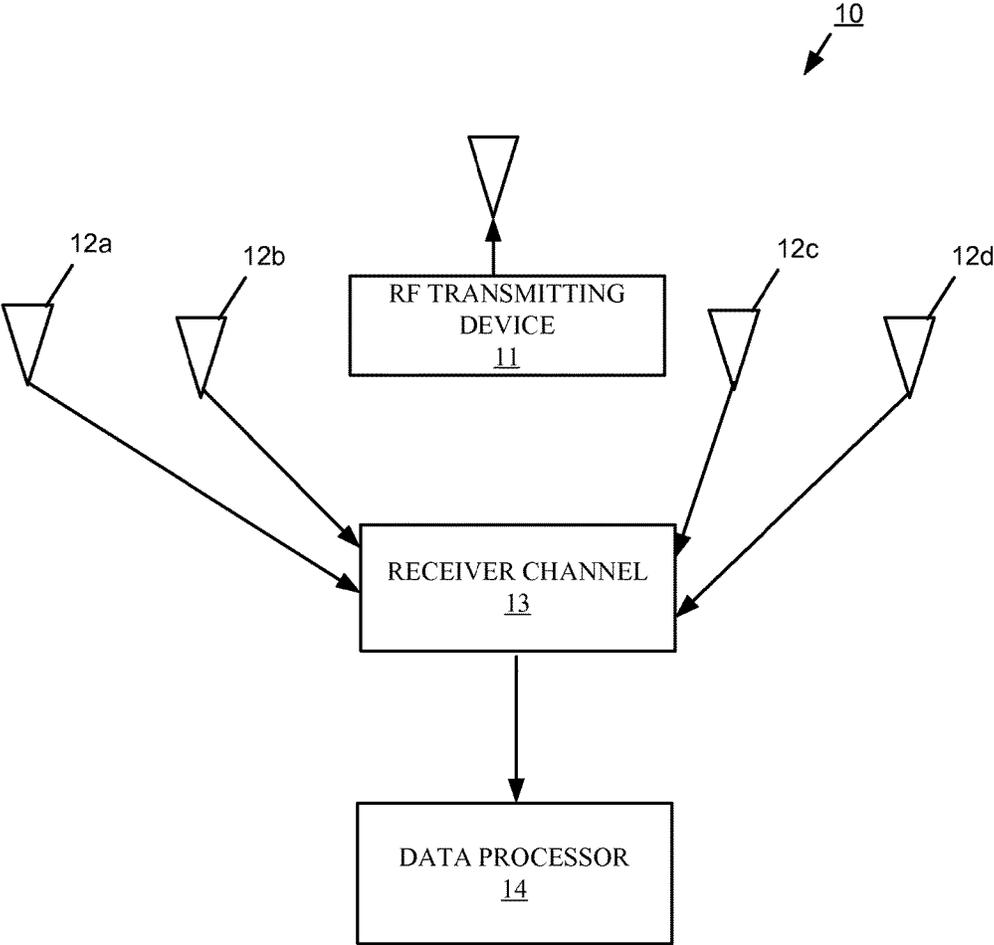


FIG. 1

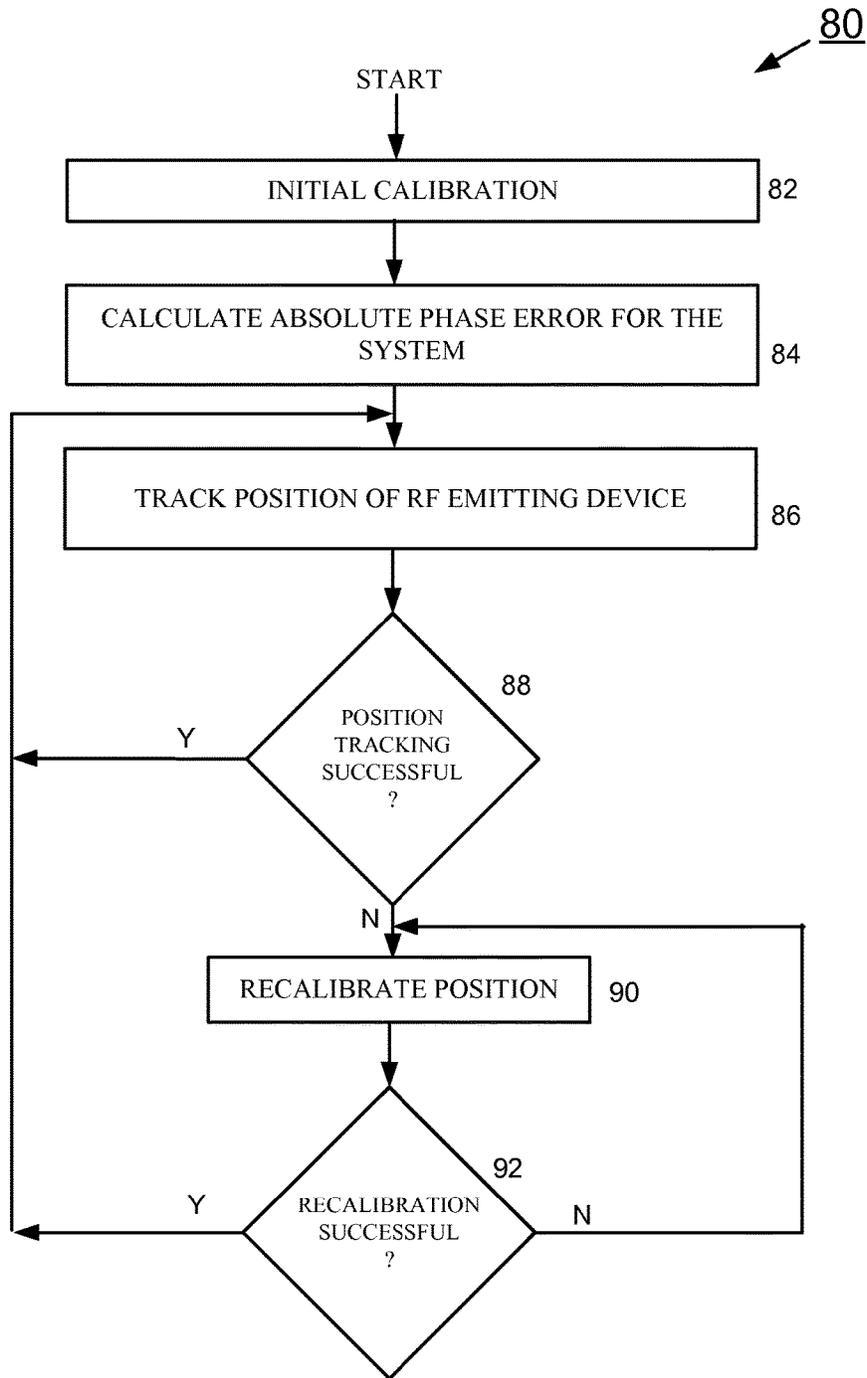


FIG. 2

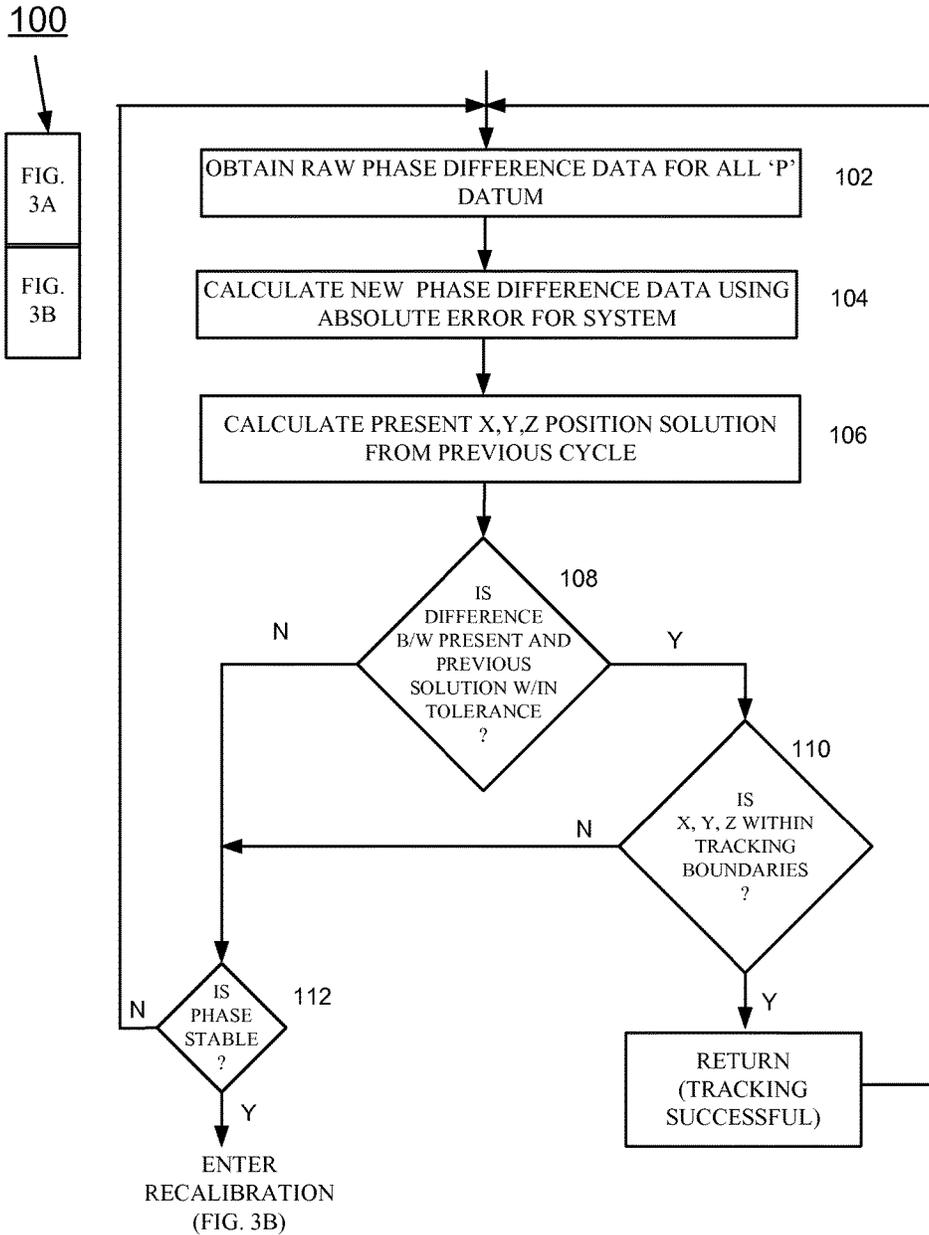


FIG. 3A

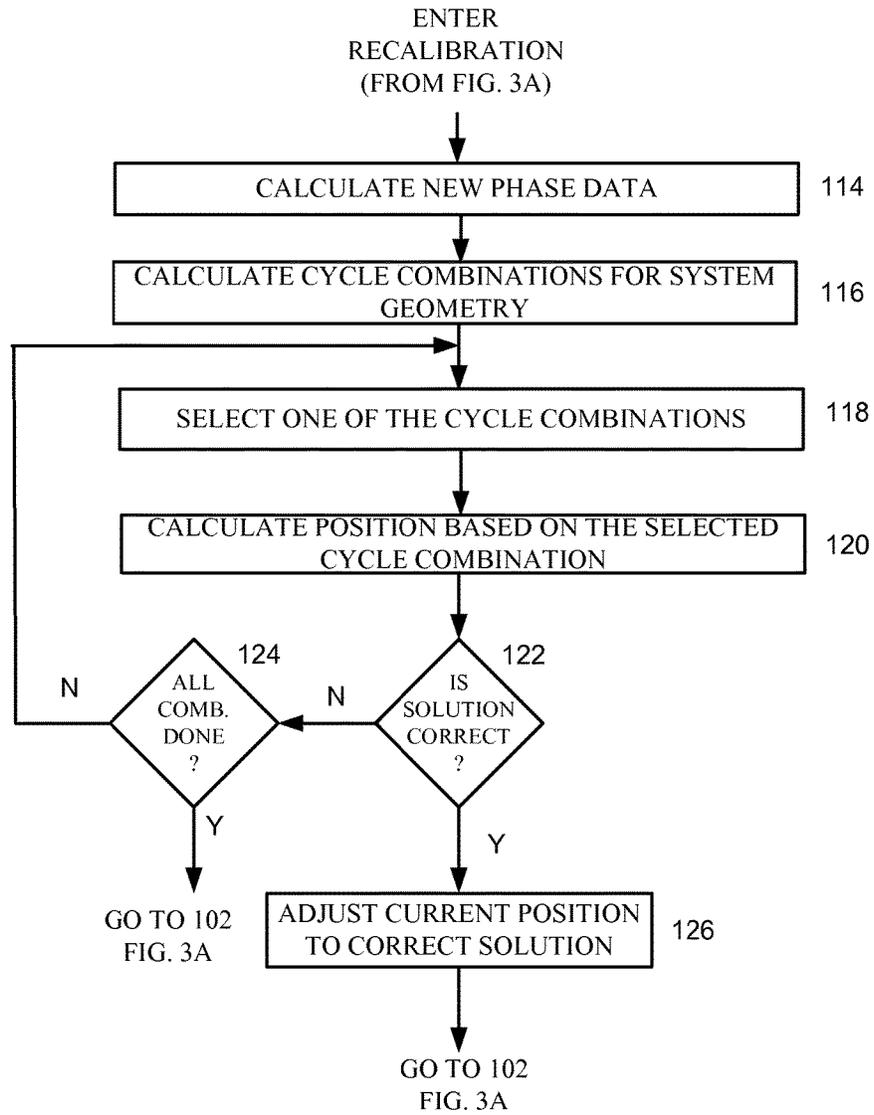


FIG. 3B

RADIO FREQUENCY COMMUNICATION SYSTEM

RELATED APPLICATION

This application claims the benefit of and priority to U.S. provisional application No. 61/692,787, filed Aug. 24, 2012, titled "Radio Frequency Communication System," the entirety of which is incorporated by reference herein.

FIELD OF THE INVENTION

The invention relates generally to systems and methods of radio frequency (RF) communication. More particularly, the invention relates to systems and methods for tracking the position of RF transmitting devices.

BACKGROUND

A commonly used method to track the position of a radio signal transmitting device is to use the time difference of arrival (or, equivalently, the phase difference of arrival) at various receivers or receiver antennae (receivers) disposed at known locations, to determine the position of the RF transmitting device. By solving the non-linear equations associated with such systems, the position of the RF transmitting device can be determined. Because phase (θ) and time (t) are related by $\theta = \omega t$, where ω is a scalar, phase and time are equivalent systems and subsequent descriptions are denoted by time or time differences, as appropriate.

Typically, position tracking systems require at least three or four receivers at known positions to determine a two-dimensional or three-dimensional position recording of the RF transmitting device. An example of an embodiment can contain a receiver channel that includes one antenna, one receiver, phase correlation circuitry for comparing the RF transmitting device signal's time difference of arrival, ADC circuitry, and a processor for processing the timing data. Many tracking systems use just one processor that receives data from each receiver channel with each receiver channel including both receiver hardware and the antenna.

Certain computer-based applications track the position of an interactive peripheral device (i.e., RF transmitting device) and use that position data to engage a software program requiring high tracking accuracy. In these applications, the RF transmitting device is registered with screen images provided by software. To make this RF transmitting device's operation effective for a user (e.g., to control a cursor on a screen) highly accurate positions are required to provide realistic interaction between the user operating the RF transmitting device and the software program. A signal time of arrival comparison approach for RF transmitting device tracking can provide these higher accuracies.

A problem with such position tracking systems is the reduction in accuracy due to multipath interference and other line-of-sight blockage issues. Multipath interference is a phenomenon whereby a wave from a source travels to a detector via two or more paths and causes the detector to receive two (or more) components of the wave. Complete line-of-sight blockage can occur when an object comes between the source and detector. During a multi-player game, for example, one player can inadvertently block the transmitter used by another player.

SUMMARY

In one aspect, the invention features a method of recovering from a lost position in a position tracking system. The

method comprises tracking a position of a radio frequency (RF) transmitting device based on RF signals emitted by the RF-transmitting device. If the tracking loses the position of the RF-transmitting device, new phase difference data are calculated from RF signals transmitted by the RF-transmitting device and received at four or more antennas, for use in recovering the position of the RF transmitting device. A subset of candidate position solutions for evaluation is identified based on the new phase difference data. One or more of the candidate position solutions in the subset are evaluated to find an acceptable position solution. The tracking of the position of the RF-transmitting device resumes using the acceptable position solution.

In another aspect, the invention features a position tracking system for recovering from a failure during position tracking of an RF-transmitting device. The position tracking system comprises a network of four or more spatially separated antennas fixed at different locations. The four or more antennas receive RF signals sent from the RF-transmitting device. A first processor is programmed to calculate a position of RF-transmitting device based on time of arrival information of the RF signals received by the four or more antennas. A data processor is programmed to calculate, if tracking of the position of the RF-transmitting device becomes lost, new phase difference data from the RF signals transmitted by the RF-transmitting device and received at the four or more antennas, for use in recovering the position of the RF transmitting device. The data processor is further programmed to identify a subset of candidate position solutions for evaluation based on the new phase difference data, evaluate one or more of the candidate position solutions in the subset to find an acceptable position solution, and to resume the tracking of the position of the RF-transmitting device using the acceptable position solution.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing an embodiment of a position tracking system with position recalibration capabilities.

FIG. 2 is a flowchart of an embodiment of a process for tracking the position of an RF-transmitting device, including a position recalibration process for reestablishing position should position becomes momentarily lost.

FIG. 3A and FIG. 3B are flowcharts of an embodiment of the position recalibration process.

DETAILED DESCRIPTION

Systems and methods described herein can effectively improve the performance of position tracking of RF transmitting devices by recovering from multipath interference and line-of-sight blockages. An RF communication system tracks the physical position of a wireless RF transmitting peripheral device (e.g., a computer mice, game controllers, etc.). An example embodiment of the RF communication system includes: a receiver network of four or more (for three-dimensional tracking) receiver antennae fixed at known physical positions that receive radio transmissions from one or more wireless mobile transmitters or RF transmitting devices; one or more receivers connected to the receiver antennae; a data processor that computes the relative position of each RF transmitting device through time difference of arrival between a reference receiver and all

other receiver antennae. In the RF communication system, the data processor can compute the relative position of each RF transmitting device in two-dimensional or three-dimensional space by comparing the time of arrival at each receiver antenna with the reference receiver and correlating those time differences with the known physical position of each antenna to determine the position of the RF transmitting device.

For example, in one configuration for three-dimensional RF transmitting device position tracking, an RF transmitting device transmits an RF signal that is received by at least four receiver antennae. One receiver antenna acts as the reference antenna to compare the time difference of arrival of the RF transmitting device's RF signal at each of the other three receiver antennae. This timing information and the antennas' known positions allow the RF communication system, through triangulation or trilateration techniques, to determine the physical position of the RF transmitting device. Other techniques for calculating the position of the RF-transmitting device are described in U.S. patent application Ser. No. 13/079,800, filed Apr. 4, 2011, titled "Multiplexing Receiver System", the entirety of which application is incorporated by reference herein.

The receiver channel may or may not include a data processor, depending on application needs. For example, in a game console application, manufacturers may want data processing (with position calculation) to occur in the console processor that enables the receiver channel to end at the ADC circuit. In such an embodiment, the processor is separate from the receiver channel.

When the RF communication system operates with a RF transmitting device that transmits RF signals having a wavelength λ greater than the tracking distance from the receiver antennas, a single solution to the tracking algorithm is available. However, when the RF signals have a wavelength λ much smaller than the tracking distance, multiple position solutions to the tracking algorithm are possible. Because of the possibility of a multiple position solution, a tracking algorithm that uses cycle counts (i.e., full wavelengths) is preferable. This type of tracking algorithm starts at a known position solution and keeps track of the phase by adding or subtracting cycles appropriately as the position changes.

FIG. 1 shows an embodiment of a wireless position tracking system 10 including a transmitter 11 (RF transmitting device) carried by/attached to/embedded on an object whose position (x, y, z) is to be determined, a receiver network including the receiver channel's antennae 12a through 12d (generally 12), whose relative positions (X_i, Y_i, Z_i) are known, a receiver channel 13 and a data processor 14. At least four receiver antennae and one transmitter are required for determining the three-dimensional transmitter position within the tracking environment. In position tracking system 10, the received signal (e.g., Code Division Multiple Access or CDMA) is sent to the receiver channel unit 13. The data obtained from receiver channel 13 are sent to the data processor 14. From the data, the data processor 14 calculates the position (x, y, z) of the RF transmitting device and can display that position on a computer screen, or provide the position to other applications for use.

In one embodiment, the data processor 14 calculates the position of the RF transmitting device by using equations with the known relative three-dimensional positions of the receiver antennae. An example of the tracking equations, where the subscript 1 represents the reference receiver antenna, follows:

$$f_1 = \frac{\sqrt{(x_2-x)^2 + (y_2-y)^2 + (z_2-z)^2} - \sqrt{(x_1-x)^2 + (y_1-y)^2 + (z_1-z)^2}}{\quad} \quad (\text{Eq. 1.})$$

$$f_2 = \frac{\sqrt{(x_3-x)^2 + (y_3-y)^2 + (z_3-z)^2} - \sqrt{(x_1-x)^2 + (y_1-y)^2 + (z_1-z)^2}}{\quad} \quad (\text{Eq. 2.})$$

$$f_3 = \frac{\sqrt{(x_4-x)^2 + (y_4-y)^2 + (z_4-z)^2} - \sqrt{(x_1-x)^2 + (y_1-y)^2 + (z_1-z)^2}}{\quad} \quad (\text{Eq. 3.})$$

where (x_i, y_i, z_i, i=1,2,3,4) are the positions of the receiver antennae and (x, y, z) is the position of the RF transmitting device being determined, f₁, f₂ and f₃ are the measured differences in distance, respectively, between antennae 1 and 2, antennae 1 and 3 and antennae 1 and 4. These equations can be solved using a Kalman filter or a least squares minimization algorithm to determine the position solution.

FIG. 2 shows an embodiment of a process 80 for tracking the position of an RF transmitting device, including a position recalibration in the event the positing tracking process loses track of the device's position. In a description of the process 80, reference is made to the elements of FIG. 1. At step 82, an initial calibration is performed on the RF communication system 10. During the initial calibration, the RF transmitting device 11 is disposed at a known location. An absolute phase error is calculated (step 84) for all phase difference data between each antenna and the reference antenna, by using the present position solution from step 82 and changing the position into phase data using the known signal wavelength λ (for example, a transmitted 2.4 Ghz RF signal has approximately a 0.125 m wavelength). In general, the absolute phase error is equal to: $360 * (\text{distance}\{k\} - \text{distance}\{k-1\}) / \lambda - \text{observation}\{k\}$, where $\text{distance}\{k\}$, where $k=1,2,3,4, \dots$ represents the distance between the RF transmitting device and antenna k, and where $\text{distance}\{k-1\}$, where $k=1,2,3,4, \dots$ represents the distance between the RF transmitting device and antenna k-1, and where $\text{observation}\{k\}$ represents the current phase difference measurement.

At step 86, the RF communication system 10 tracks the position of the RF transmitting device 11, as described in connection with FIG. 1. The process 80 continues to track position for as long as the position tracking remains (step 88) successful. If the position tracking fails, the process 80 attempts (step 90) to perform position recalibration. If position recalibration succeeds (step 92), the position tracking resumes using the recalibrated position. Attempts to recalibrate position can continuously loop until success occurs, or until persistent failure dictates other corrective action, such as rebooting.

FIG. 3A and FIG. 3B show an embodiment of a process 100 for position tracking that includes position recalibration in the event the position of the RF-transmitting device become lost. Position recalibration can be incorporated into the basic tracking algorithm (FIG. 2), which solves the equations above using least squares, Kalman filtering, or other techniques known in the art. In the description of this process 100, reference is made to the elements of FIG. 1. In one embodiment, data processor 14 performs the calculations herein described. As is known in the art, these calculations can be performed elsewhere, in other associated processing means. In block 102, the receiver channel 13 obtains raw (unprocessed) phase difference data from the antennas 12. From this phase difference data, the data processor 14 calculates (step 104) new phase difference data, which includes the time difference of arrival between each antenna and the reference antenna, using the absolute phase

difference error of the system 10 (step 84, FIG. 2). From this new phase difference data, the data processor 14 calculates (step 106) a present position of the RF-transmitting device. Additionally, the data processor 14 has access to the position solution from the previous position calculation cycle.

Validation of the position solution then occurs. Based on the success or failure of the validation, the position tracking process 100 either returns to the tracking algorithm (step 86, FIG. 2), or performs a position recalibration process (step 90, FIG. 2). The first validation (step 108) checks whether the previous and present solution differ by a predetermined tolerance (toll). For example, the validation can perform the tolerance test as follows: Does $\|x[p]-x[p-1]\| < \text{toll}$, and $\|y[p]-y[p-1]\| < \text{toll}$, and $\|z[p]-z[p-1]\| < \text{toll}$, where $[p]$ is the present solution, $[p-1]$ is the previous solution, x , y , and z are the position coordinates, and toll is the predefined tolerance (i.e. 0.01 meters)? Although only one tolerance (toll) is noted, each solution component could have a different tolerance. In addition, the tolerance can vary, based on other criteria, for example, varying with the velocity of the RF transmitter.

A second validation verifies (step 110) whether the present position solution is within an acceptable tracking volume. The user or manufacturer of the tracking system can define this tracking volume, which serves to place realistic limits on the tracking solution. For example, it can be determined that a tracking position beyond $z=4$ meters results in unreliable position determination due to signal drop off. Accordingly, $z=4$ can then be one of the limits placed on the viable tracking volume.

If either of the first and second validation fails, signifying that position tracking has failed, the process 100 determines (step 112) whether the phase is stable. After position tracking fails, the position recalibration can occur only with stable phase data, such as occurs when the RF-transmitting device is held steady. The process of determining a stable phase includes acquiring and analyzing new phase data for a predetermined number of samples and confirming that the phase has stayed relatively constant across these samples. The definition of "stable," and the length of time that stability is maintained, can be programmable or based on known conditions. Looping through the two validations (108, 110) and the phase stability process (112) can continue indefinitely until all conditions are met to satisfy the recalibration requirements.

FIG. 3B shows the position recalibration process, which calculates new phase difference data by adding the absolute phase error of the system (step 84, FIG. 2) to the raw phase difference data obtained in step 102, FIG. 3A. ($\text{New_phase}\{p\} = \text{absolute_phase_error}\{p\} + \text{raw_phase_data}\{p\}$). The new phase data is converted to cyclic data so that the resulting phase data is between ± 180 degrees. ($\text{New_phase}\{p\} = \text{New_phase}\{p\} - 360^\circ \cdot \text{round}(\text{New_phase}\{p\} / 360^\circ)$).

After the new phase difference data are calculated, the possible position solutions are calculated. Because the normal position solution space is vast when the wavelength λ is much smaller than the tracking distance, some means of checking only viable possible solutions serves to greatly reduce the number of candidate position solutions, and, thus, facilitate processing performance. One embodiment reduces the number of candidates by calculating position solutions based on the geometry of the receiver antennae and the new phase difference data. For example, a gridded search over a predefined volume surrounding the last known position can be used to evaluate phase measurements against the anticipated phase measurements. Only "k" position solutions that

yield an integer number of cycles (i.e., are an integer number of wavelengths) from the last known position in any x , y , z direction are selected (step 116) as candidates for evaluation. These "k" candidate position solutions, also referred to as cycle combinations, are saved for use in steps 118, 120, 122, and 124.

In one embodiment, the position recalibration process seeks a first correct (i.e., acceptable) solution. At step 120, one of the "k" candidate position solutions is selected. This candidate position is evaluated (e.g., using a least squares position algorithm). This can be the same least squares position algorithm used during normal position tracking; alternatively, the least squares position algorithm can be custom specific to this operation; or this least squares position algorithm can be programmable to accommodate either one. The position solution from the least squares algorithm is evaluated in block 122. Evaluation can consist of various metrics, including, for example, the size of the residual errors, and the location of the position solution, or combinations thereof, as is known in the art. If the candidate position solution is found to be acceptable, position recalibration is considered successful; control returns to the position-tracking process (FIG. 2, block 86), with the acceptable position solution becoming (step 126) the current position of the RF-transmitting device from which the tracking process resumes. Otherwise, the next "kth" cycle combination is selected in block 118 for evaluation in the least squares routine. This loop continues (step 124) until either an acceptable candidate position solution is found or all "k" cycle combinations have been evaluated. If all "k" combinations are evaluated and found unacceptable, a new set of raw phase data (FIG. 3A, block 102) is obtained, after which, phase stability is retested (provided position determination continues to fail in steps 108 or 110), and the recalibration section of the process is re-entered. As an alternative technique, all "k" candidate position solutions can be tested first before selecting a best position solution and returning that best position solution to the position tracking process.

As will be appreciated by one skilled in the art, aspects of the present invention may be embodied as a system, method, and computer program product. Thus, aspects of the present invention may be embodied entirely in hardware, entirely in software (including, but not limited to, firmware, program code, resident software, microcode), or in a combination of hardware and software. All such embodiments may generally be referred to herein as a circuit, a module, or a system. In addition, aspects of the present invention may be in the form of a computer program product embodied in one or more computer readable media having computer readable program code embodied thereon.

The computer readable medium may be a computer readable storage medium, examples of which include, but are not limited to, an electronic, magnetic, optical, electro-magnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination thereof. As used herein, a computer readable storage medium may be any non-transitory, tangible medium that can contain or store a program for use by or in connection with an instruction execution system, apparatus, device, computer, computing system, computer system, or any programmable machine or device that inputs, processes, and outputs instructions, commands, or data. A non-exhaustive list of specific examples of a computer readable storage medium include an electrical connection having one or more wires, a portable computer diskette, a floppy disk, a hard disk, a random access memory (RAM), a read-only memory (ROM), a USB flash drive, an

non-volatile RAM (NVRAM or NOVRAM), an erasable programmable read-only memory (EPROM or Flash memory), a flash memory card, an electrically erasable programmable read-only memory (EEPROM), an optical fiber, a portable compact disc read-only memory (CD-ROM), a DVD-ROM, an optical storage device, a magnetic storage device, or any suitable combination thereof. A computer readable storage medium can be any computer readable medium that is not a computer readable signal medium such as a propagated data signal with computer readable program code embodied therein.

Program code may be embodied as computer-readable instructions stored on or in a computer readable storage medium as, for example, source code, object code, interpretive code, executable code, or combinations thereof. Any standard or proprietary, programming or interpretive language can be used to produce the computer-executable instructions. Examples of such languages include C, C++, Pascal, JAVA, BASIC, Smalltalk, Visual Basic, and Visual C++.

Transmission of program code embodied on a computer readable medium can occur using any appropriate medium including, but not limited to, wireless, wired, optical fiber cable, radio frequency (RF), or any suitable combination thereof.

The program code may execute entirely on a user's device, partly on the user's device, as a stand-alone software package, partly on the user's device and partly on a remote device or entirely on a remote device. Any such remote device may be connected to the user's device through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external device (for example, through the Internet using an Internet Service Provider).

Additionally, the methods of this invention can be implemented on a special purpose computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element(s), an ASIC or other integrated circuit, a digital signal processor, a hard-wired electronic or logic circuit such as discrete element circuit, a programmable logic device such as PLD, PLA, FPGA, PAL, or the like.

Furthermore, the disclosed methods may be readily implemented in software using object or object-oriented software development environments that provide portable source code that can be used on a variety of computer or workstation platforms. Alternatively, the disclosed system may be implemented partially or fully in hardware using standard logic circuits or a VLSI design. Whether software or hardware is used to implement the systems in accordance with this invention is dependent on the speed and/or efficiency requirements of the system, the particular function, and the particular software or hardware systems or microprocessor or microcomputer systems being utilized. The methods illustrated herein however can be readily implemented in hardware and/or software using any known or later developed systems or structures, devices and/or software by those of ordinary skill in the applicable art from the functional description provided herein and with a general basic knowledge of the computer arts.

While this invention has been described in conjunction with a number of embodiments, it is evident that many alternatives, modifications and variations would be or are apparent to those of ordinary skill in the applicable arts. Accordingly, it is intended to embrace all such alternatives, modifications, equivalents, and variations that are within the spirit and scope of this invention.

What is claimed is:

1. A method of recovering from a lost position in a position tracking system, comprising:
 - tracking a position of a radio frequency (RF) transmitting device based on RF signals transmitted by the RF-transmitting device and received at four or more antennas;
 - determining that tracking the position of the RF-transmitting device has failed by comparing a present position of the RF transmitting device with a previous position of the RF transmitting device and determining that a difference between the present position and previous position exceeds a predefined tolerance;
 - recalibrating the position tracking system to recover the position of the RF-transmitting device in response to determining that tracking the position of the RF-transmitting device has failed by:
 - calculating phase difference data, in a time domain, from RF signals transmitted by the RF-transmitting device and received at the four or more antennas;
 - based on the calculated phase difference data, calculating a plurality of candidate position solutions;
 - identifying and retaining a subset of candidate position solutions from the plurality of candidate position solutions for evaluation, each candidate position solution in the subset being an integer number of wavelengths away from a last known position of the RF-transmitting device;
 - evaluating at least one of the candidate position solutions in the subset using a least squares position algorithm; and
 - based on the evaluation, selecting one of the candidate position solutions in the subset; and
 - resuming the tracking of the position of the RF-transmitting device using the selected candidate position solution as a current position of the RF-transmitting device.
2. The method of claim 1, wherein determining that the tracking of the position of the RF-transmitting device has failed includes comparing the present position of the RF transmitting device with boundary conditions.
3. The method of claim 1, further comprising verifying phase stability before attempting to recover the position of the RF-transmitting device.
4. The method of claim 1, further comprising:
 - calculating absolute phase difference data errors; and
 - adjusting the phase difference data based on the absolute phase difference data errors; and
 - adjusting the adjusted phase difference data to fall within specific bounds.
5. The method of claim 1, wherein evaluating one or more of the candidate position solutions in the subset with a least squares algorithm includes evaluating the one or more of the candidate position solutions with a Kalman algorithm.
6. An RF-transmitting device, comprising:
 - a network of four or more spatially separated antennas fixed at different locations, the four or more antennas receiving RF signals sent from the RF-transmitting device; and
 - a data processor programmed to calculate, in a time domain, a position of the RF-transmitting device based on time of arrival information of the RF signals received by the four or more antennas, the data processor being further programmed to:
 - determine that the position of the RF-transmitting device is lost by comparing a present position of the RF-transmitting device with a previous position of the RF transmitting device, and determining that a

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difference between the present position and previous position exceeds a predefined tolerance; and
 recover the position of the RF-transmitting device in response to determining the position of the RF-transmitting device is lost by calculating phase difference data from the RF signals transmitted by the RF-transmitting device and received at the four or more antennas, calculating a plurality of candidate position solutions based on the calculated phase difference data, identifying and retaining a subset of candidate position solutions for evaluation, each candidate position solution in the subset being an integer number of wavelengths away from a last known position of the RF-transmitting device, evaluating at least one of the candidate position solutions in the subset using a least squares position algorithm, selecting one of the candidate position solutions in the subset based on the evaluation, and resuming the tracking of the position of the RF-transmitting device

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using the selected candidate position solution as a current position of the RF-transmitting device.

7. The position tracking system of claim 6, wherein in determining that the position of the RF-transmitting device is lost, the data processor is further programmed to compare the present position of the RF transmitting device with boundary conditions.

8. The position tracking system of claim 6, wherein the data processor is further programmed to verify phase stability before attempting to recover the position of the RF-transmitting device.

9. The position tracking system of claim 6, wherein the data processor is further programmed to calculate absolute phase difference data errors, adjust the phase difference data based on the absolute phase difference data errors, and adjust the adjusted, phase difference data to fall within specific bounds.

10. The position tracking system of claim 6, wherein the least squares algorithm is a Kalman algorithm.

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